

Eureka Journal of Computing Science & Digital Innovation (EJCSDI)

ISSN 2760-4993 (Online) Volume 2, Issue 5, May 2026



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FUNCTIONAL MODULES OF THE SYSTEM FOR PREDICTING FIRE RISK OBJECTS

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Abstract

This article analyzes the functional modules of a predictive system aimed at early detection and assessment of fire hazard objects. The study examines in detail the main components of the system, including data collection, processing, risk assessment, model building, and visualization modules. It also highlights effective methods for determining fire hazard using sensors, remote sensing data, and artificial intelligence algorithms. The proposed system allows for real-time monitoring, risk forecasting, and rapid decision-making. As a result, it helps prevent fires, reduce their negative consequences, and increase the effectiveness of security.

Keywords: Fire safety, prediction, model, artificial intelligence, machine learning methods, evaluation, parameters, control, decision making.

1 INTRODUCTION

Nowadays, the increasing risk of fires in industrial facilities, forestry, agricultural areas and settlements is one of the urgent problems. Climate change, the human factor, man-made impacts and the complexity of infrastructure are further increasing the likelihood of fires. Therefore, it is important not only to eliminate fires after they occur, but also to predict them in advance and take preventive measures. Modern information technologies, in particular, artificial intelligence, remote sensing and geographic information systems (GIS), are creating wide opportunities for early detection and monitoring of fire risks. These technologies



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allow for rapid analysis of large volumes of data, monitoring of environmental parameters and determining the level of risk. In particular, real-time predictive systems are considered an important tool in reducing fire risks.

The main objective of this work is to study the functional modules of a predictive system for identifying and assessing fire hazard objects and analyze their mutual integration. This system includes such important stages as data collection, processing, risk assessment and visual presentation of results. As a result, the proposed approach serves to effectively manage fire risk, make quick decisions and prevent emergency situations [1, 2].

2 METHODS AND RESULTS

A wide scientific school has been formed by foreign scientists in the field of fire hazard prediction and modeling, which are mainly based on physical, empirical and hybrid models. American scientist Richard C. Rothermel is considered one of the founders of the field of fire modeling. The model developed by him in 1972: calculates the rate of fire spread based on the energy balance, takes into account combustible material, wind and terrain, and forms the basis of modern systems (BEHAVE, FARSITE). His model is still widely used in practical systems today and has not lost its relevance for more than half a century.

The FARSITE model developed by Mark A. Finney allows for computer simulation of fire spread: it models fire development in time and space, integrates meteorological and GIS data, and is used to forecast real and potential fires. This model is based on the Rothermel equation and is an important step in turning it into a practical system.

The NEXUS system was developed by J. Scott and E. Reinhardt: it assesses the risk of crown fire, introduces indicators such as the “Torching Index” and “Crowning Index”, and allows for a comprehensive assessment of fire risk.

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The methods used to predict fire hazard properties within the scope of this research work cover several scientific and technological areas. The main methods are systematically presented below:

1. Statistical and probabilistic methods.
2. Artificial intelligence and machine learning methods.
3. Remote sensing methods.
4. Analysis based on geographic information systems (GIS).
5. Physical and empirical models.
6. Sensor and IoT (Internet of Things) technologies.
7. Hybrid (combined) approaches.

To achieve the highest accuracy, a combination of methods is usually used, rather than a single method. In particular, the integration of artificial intelligence, GIS, and remote sensing forms the basis of modern fire risk prediction systems [3, 4]. Taking into account the conducted analyses and the principles of developing modern information systems in the field, a general structure of a system for predicting the occurrence of fire hazards in high-risk facilities was developed (Figure 1).

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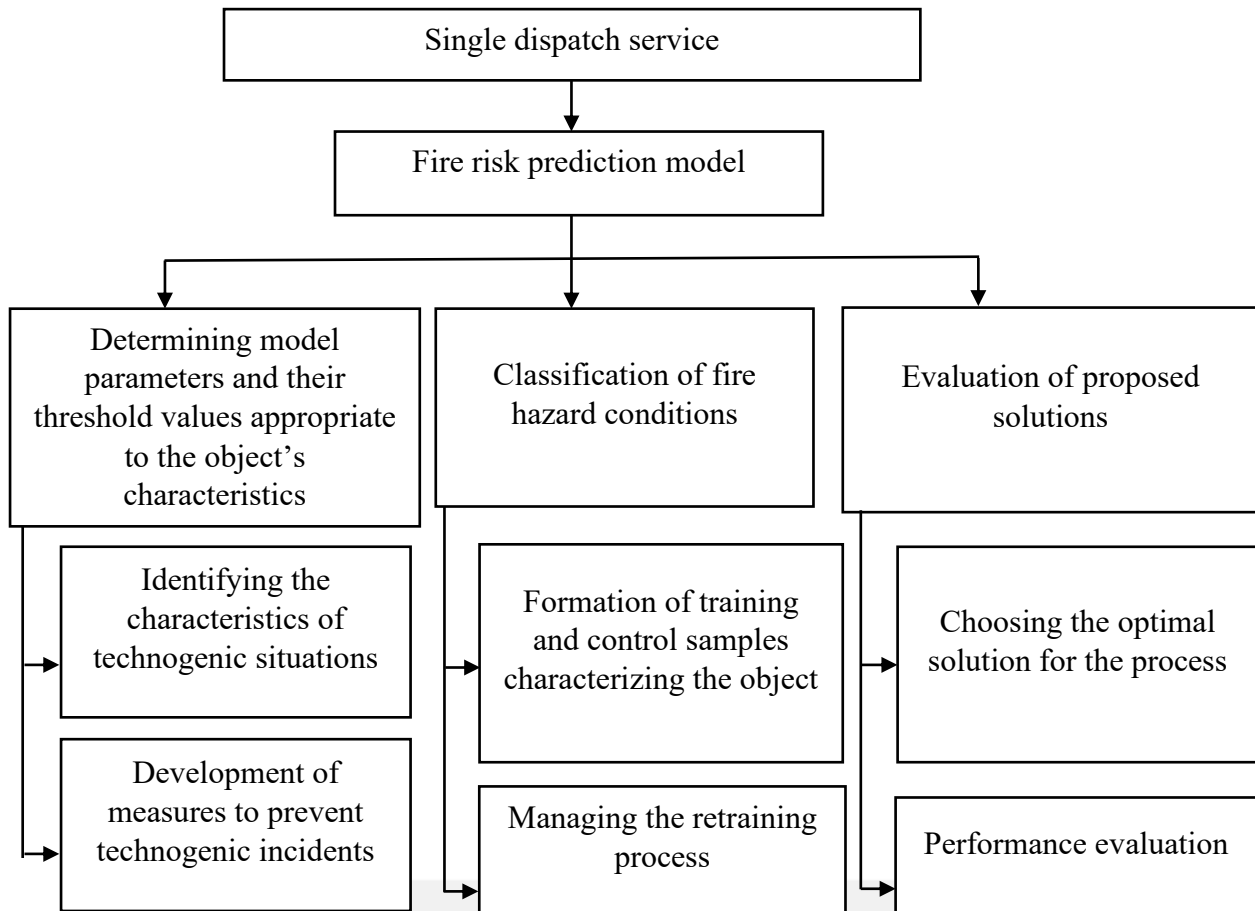


Figure 1. General structure of a system for predicting the occurrence of fire hazards in high-fire risk facilities

One of the main tasks of the fire risk prediction system is to select measures aimed at ensuring fire safety. It is also to provide the decision-maker with detailed information on the fire safety situation, taking into account the fire risk assessment for each of the proposed solutions, and to make a final decision [5, 6]. The structural scheme of the fire risk prediction system for facilities with high fire risk is determined based on its tasks (Figure 2).

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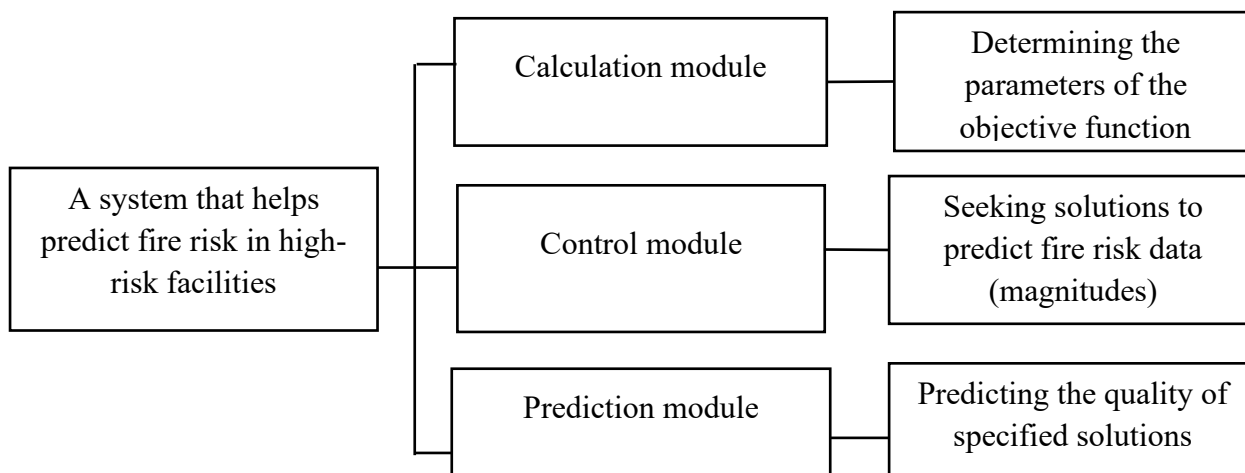


Figure 2. Structural diagram of a system supporting the fire risk prediction system in high-fire risk facilities

Also, the process that helps predict fire risk consists of 3 modules, the description of its structure by modules is as follows:

The calculation module serves as a tool that allows you to assess the effectiveness of the recommended measures using the parameters of the objective function, which may include fire hazard indicators of the protected object, economic efficiency indicators, etc. The initial data is entered based on technical documentation for engineering structures located at the object, statistics of technological equipment failures, information on combustible substances in the protected object, and other necessary parameters.

As a rule, when assessing fire risk indicators, all engineering systems that can affect the probability and consequences of fire risk are taken into account. Such engineering systems include: fire alarm systems, fire extinguishing systems, warning and evacuation control systems, flood control devices, etc.

When analyzing the impact of fire risk on employees of a protected object and people living in a residential area, the probability of their presence at a certain point in the territory is taken into account, as well as the location of this point



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relative to hazardous technological devices, the consequences of possible fire risks and the frequency of their impact. A system that helps predict fire risk can take into account engineering systems aimed at reducing fire risk or reducing possible damage in the event of accidents, depending on the situation that arises when modeling fire situations in different parts of the territory under consideration.

Management module. The task of the management module is to find solutions aimed at ensuring fire safety based on a risk-based approach by simply enumerating possible options or using intelligent optimization methods. This module contains a database that stores fire safety activities. During operation, the management module interacts with the user and has full access to all system functions, input data and risk calculation results. During operation, it is possible to add fire protection systems aimed at reducing the likelihood of fire hazards or reducing the likelihood of possible damage in the event of accidents. When modeling a fire in different parts of the territory of the protected object, parameters can be changed depending on the situation that arises. After receiving a command from the user to start the procedure for searching for measures aimed at reducing the calculated values of fire risk, the control module makes changes adapted to the project under consideration, performs the necessary calculations, assesses the quality of the results. Also, taking into account the value of the objective function, displays a report through the control module for making a final decision.

The control module has a graphical interface and provides the user with information about the proposed solutions aimed at reducing fire risk. Using the management module, the decision-maker can assess the fire situation for each proposed solution, as well as assess the economic feasibility of each solution and select the final solution. The system works until the process of selecting fire risk prediction measures is completed, after which information about the selected measures is stored in the database. In the future, this information can be used both

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to evaluate the actions of the specialist performing the fire risk prediction, and to process and develop rules for forming a knowledge base. In case of detection of unacceptable fire risk data, the management support system sends information to the decision-maker about the need to apply additional fire risk prediction measures. Once the decision-maker has adopted the final solution, it will be possible to make changes to the fire safety system of a facility with a high fire risk [7, 8, 9].

These approaches are based on a classical mathematical model and produce results that are understandable and easy to interpret.

The logistic regression model is as follows. It estimates the probability of fire occurrence $P(Y = 1)$ in the following form:

$$P = 1 / (1 + e^{-(\beta_0 + \beta_1 x_1 + \dots + \beta_n x_n)}) \quad (1)$$

where, x_i – factors such as temperature, wind speed, soil moisture. The advantage of this model is the ability to determine the degree of influence of each factor (through coefficients).

The main tool for spatial decision-making. Each factor (e.g. slope, land cover, distance to road) is given a weighting coefficient:

$$\text{Risk} = \sum w_i \cdot x_i \quad (2)$$

Below are mathematical formulas that are widely used in fire risk assessment and prediction. Each is used in different modules of the system (AI, GIS, physical model).

The Fire Risk Index is defined as:

$$\text{FRI} = \sum_{i=1}^n w_i \cdot x_i \quad (3)$$

where: w_i – factor weight (e.g. temperature, wind, NDVI), x_i – normalized value.

The fire spread rate (basic form of the Rothermel model) is as follows:

$$R = \frac{I_R \cdot \xi \cdot (1 + \phi_w + \phi_s)}{\rho_b \cdot \epsilon \cdot Q_{ig}} \quad (4)$$

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where: R – spread rate, ϕ_w – wind effect, ϕ_s – slope effect, ξ – propagation efficiency coefficient, ρ_b – bulk density of the combustible material, ϵ – effective heating number, Q_{ig} – heat required to start combustion (heat of pre-ignition).

Heat energy (fire intensity) is defined as follows:

$$I = H \cdot w \cdot R \quad (5)$$

where: H – heat of combustion, w – mass of combustible material, R – spread rate.

Models and methods aimed at predicting fire hazard properties require a complex, multi-stage and integrated approach. The results of the analysis show that, although statistical and probabilistic models provide a simple and understandable mechanism for assessing fire hazard, they cannot fully reflect complex nonlinear relationships. Therefore, artificial intelligence and machine learning methods provide much higher accuracy results through in-depth analysis of large-scale and multi-factorial data [10].

Below is a table of the main components and their numerical (quantitative) indicators for the “Functional modules of the fire hazard prediction system”. This table serves as a methodological basis for the design and evaluation of the system (Table 1).

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Table 1. Fire risk prediction system modules

No	Functional module name	Number of incoming data	Basic parameters	Processing speed (sec)	Accuracy (%)	Output result type
1	Data collection module	5–10	Temperature (°C), humidity (%), wind (m/s), CO ₂	0.5 – 2	95–98	Raw data
2	Data cleaning (preprocessing)	5–10	Filtering, normalization, interpolation	1 – 3	90–95	Cleaned dataset
3	Feature extraction	10–20	NDVI, NBR, LST, slope, land cover	2 – 5	88–93	Feature vectors
4	Analysis and model building (ML/AI)	10–50	ANN, Random Forest, SVM	5 – 20	85–97	Predict model
5	Risk assessment	5–15	Weighting coefficients, probability	1 – 4	87–95	Risk index (0–1)
6	Spatial Analysis (GIS Module)	10–30	Overlay, buffer, hotspot analysis	3 – 10	90–96	Risk map
7	Visualization module	3–10	Diagramma, heatmap, GIS layer	1 – 2	95–99	Charts and maps
8	Monitoring (real-time)	5–15	Sensor flow, drone images	0.1 – 1	92–98	Real-time alert
9	Decision-making module	5–10	Risk threshold, expert rules	1 – 3	90–97	Recommendations / alarm
10	Storage and management (DBMS)	1000+ writing	Big Data, cloud storage	0.5 – 2	99	Database

As can be seen from this table, the modules of the fire risk prediction system are interconnected, and each stage has different characteristics in terms of data volume, speed, and accuracy. The effectiveness of the system depends on the balance and level of integration between these modules.

A comparative analysis of various artificial intelligence algorithms in fire hazard prediction based on the above functional modules and their requirements is

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presented in the form of a table of numerical results (Table 2). The values are summarized based on typical ranges found in practical studies.

Table 2. Comparative results table based on artificial intelligence algorithms

No	Algorithm name	Number of incoming parameters	Training time (sec)	Test time (sec)	Accuracy (%)	RMSE	Preference level (1-5)	Application stage
1	Logistic regression	5-15	1 - 3	0.1 - 0.5	80 - 88	0.20	3	Risk assessment
2	Decision Tree	10-20	2 - 5	0.2 - 1	82 - 90	0.18	3	Classification
3	Random Forest	15-30	5 - 15	0.5 - 2	88 - 95	0.12	5	Basic prediction model
4	Support Vector Machine	10-25	10 - 30	1 - 3	85 - 93	0.14	4	Complex analysis
5	K-Nearest Neighbors	5-20	1 - 2	2 - 5	80 - 89	0.19	3	Simple classification
6	Artificial Neural Network (ANN)	20-50	15 - 60	1 - 3	90 - 96	0.10	5	Nonlinear predicting
7	Deep Learning (CNN)	30-100	60 - 300	2 - 6	92 - 98	0.08	5	Image analysis (RS data)
8	LSTM (Time Series)	20-60	50 - 200	2 - 5	91 - 97	0.09	5	Time series predicting
9	Gradient Boosting (XGBoost)	15-40	10 - 40	1 - 3	90 - 96	0.09	5	The most optimal model

Different artificial intelligence algorithms have their own advantages and disadvantages when it comes to predicting fire risk. Simple models (such as logistic regression or decision trees) are fast and easy to understand, but have relatively low accuracy. More sophisticated models, such as Random Forest, XGBoost, artificial neural networks, and deep learning algorithms, require more data but produce results with much higher accuracy.

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3 CONCLUSIONS

Fire hazard prediction systems are formed on the basis of modern information technologies and are an important tool for preventing emergency situations. Within the framework of this study, functional modules aimed at identifying and assessing fire hazard, their interrelationships and mechanisms of operation were analyzed. The results show that the stages of data collection (sensors, remote sensing), their processing, analysis based on artificial intelligence and visualization in a GIS environment provide high efficiency as a single integrated system.

Also, the complex application of statistical methods, machine learning algorithms, physical models and spatial analysis methods allows for more accurate fire hazard prediction. In particular, it is possible to optimize the process of obtaining rapid information and making decisions through real-time IoT and monitoring systems.

In general, the development of fire hazard prediction systems is of great importance not only in preventing fires, but also in reducing their economic and environmental damage. In the future, it is advisable to widely introduce Big Data, Deep Learning, and intelligent management systems to further improve such systems.

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